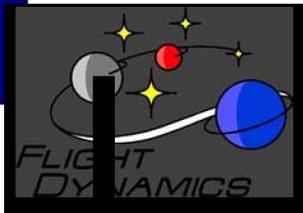


NASA'S ORBITAL DEBRIS CONJUNCTION ASSESSMENT AND COLLISION AVOIDANCE STRATEGY

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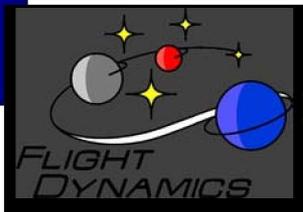
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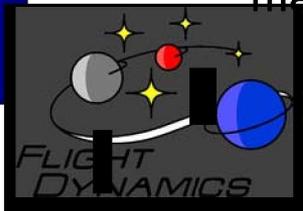
Introduction

- Over the last twenty years NASA's orbital debris avoidance strategy has tried to strike a balance between:
 - Increased safety
 - Interruption of nominal operations
- Implementation of that strategy is characterized by three periods
 - Use of a collision avoidance box by the Space Shuttle
 - Use of a probability based approach by the Space Station & Space Shuttle
 - Widespread adoption of the probability method by GSFC & others, along with numerous improvements to the probability method

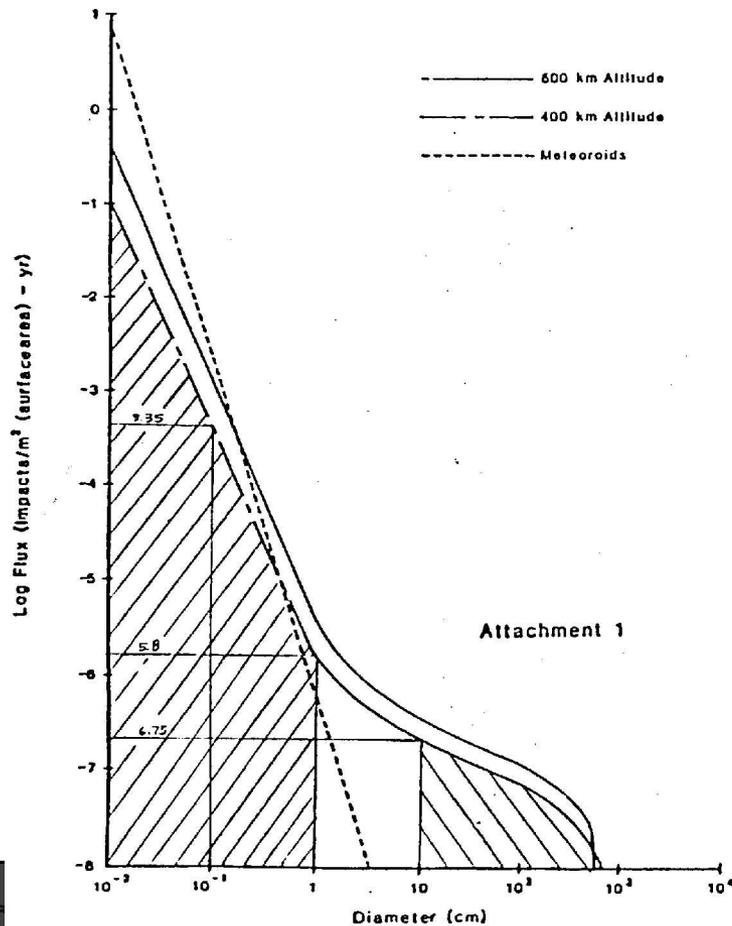


Box Method

- Protection of NASA's manned spacecraft from track-able orbital debris started as an analysis project in the late 1980's during the Shuttle Program stand-down period following the Challenger accident
- Prior to that, the Shuttle Program had determined that the orbital debris vector accuracy was too poor to justify performing an avoidance maneuver
- Therefore, the flight rules of the time stated:
 - “No action will be taken in response to (USSTRATCOM) combo conjunction predictions even if a collision is predicted”
- This led to an analysis by NASA JSC to determine what tracking accuracies would be sufficient to justify performing collision avoidance maneuvers
- The analysis addressed three factors:
 - Level of risk the Shuttle Program was willing to take
 - Shuttle tracking accuracies
 - How often the Shuttle Program was willing to perform a collision avoidance maneuver



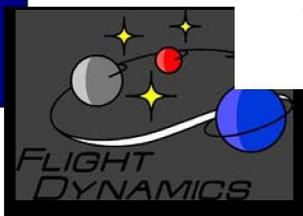
Predicted Orbital Debris Environment in the 1990's



FROM SPACE STATION
DESIGN DOCUMENT
JSC-20001

BY D. KESSLER/SN3

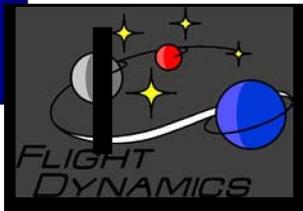
-  PROTECTED BY SHIELDING
-  NO PROTECTION
-  PROTECTED BY COLLISION AVOIDANCE



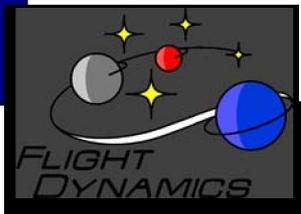
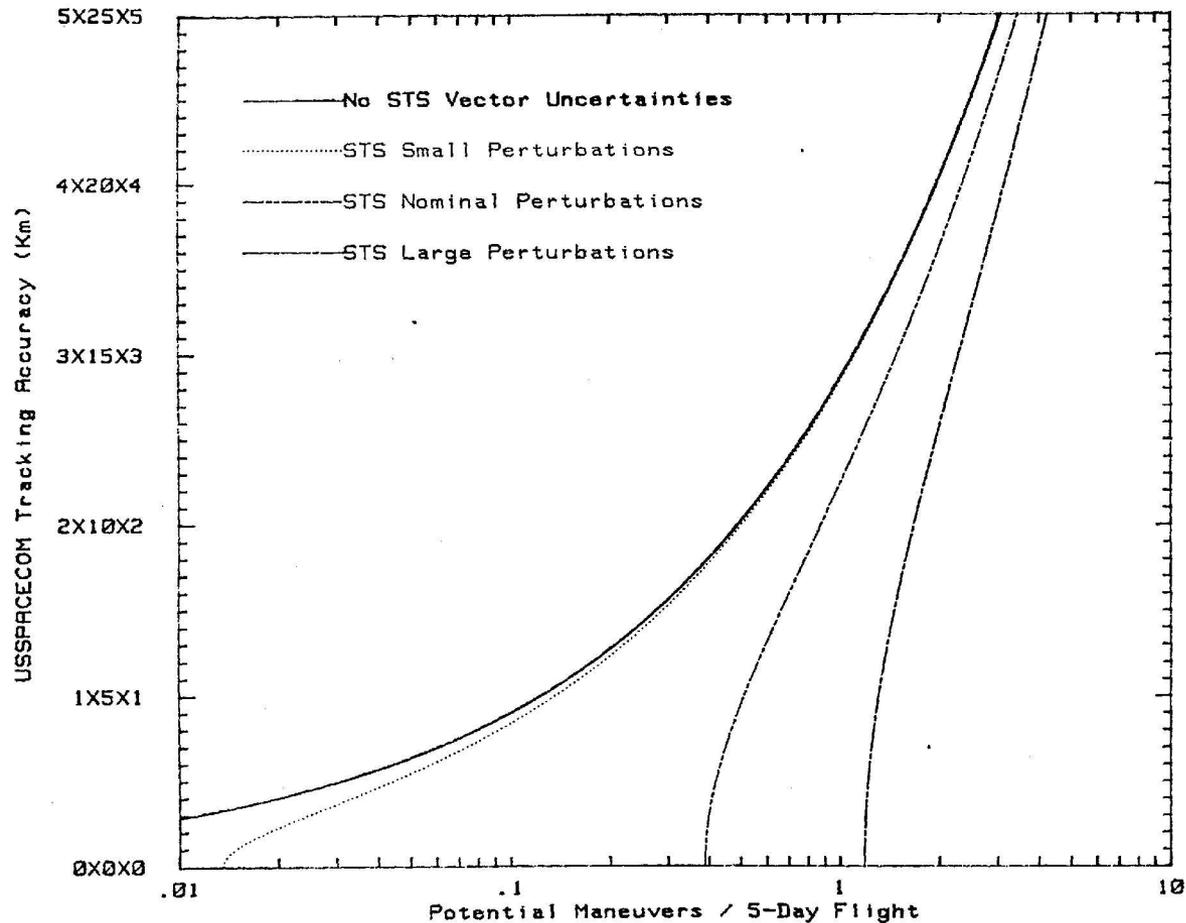
Box Method

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- Using this environmental data it was estimated that for every 5 day Shuttle flight:
 - 1 in 1,600,000 chance of being hit by an object larger than 10cm if no collision avoidance maneuver was performed
 - 1 in 180,000 for an object larger than 1cm
- A program called Probability of Collision (Pc) Predictor (PCP) was developed to calculate the debris object risks
- Parametric runs looked at a number of independent variables:
 - Space Shuttle and object uncertainties
 - miss distances
 - directions of miss distances
 - various wedge angles
- Analysis showed that for a fairly low maneuver rate, between 5 and 50 maneuvers per 100 flights depending on what risk level the Program would accept, the higher risk objects could be successfully avoided



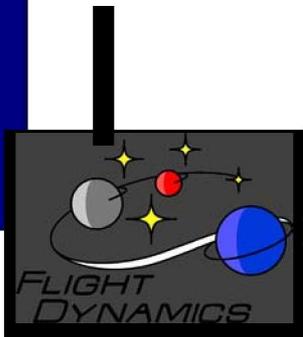
Potential Maneuvers vs. Tracking Accuracy



Box Method

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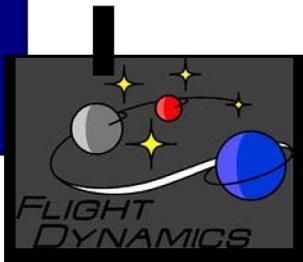
- This work led to a change to the flight rules and the adoption of a debris avoidance strategy for the first time
- The Shuttle Program chose 1 in 100,000 as an acceptable risk based on the frequency of conjunctions and the level of risk taken by other National Space Transportation System (NSTS) elements
- The new flight rule now stated
 - “A collision avoidance maneuver will be performed for a conjunction predicted by the United States Strategic Command if the predicted miss distance is less than 2 km radially, 5 km downtrack, and 2 km out-of-plane if the maneuver does not compromise either primary payload or mission objectives. Propellant red-lines will not budget for any potential maneuvers.”



Box Method

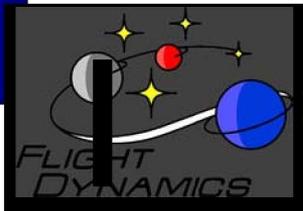
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- To implement this rule, a new process for using maneuvers for managing debris risk was collaboratively developed with USSTRATCOM and consisted of the following steps:
 - NASA JSC regularly providing Space Shuttle vectors to USSTRATCOM
 - USSTRATCOM notifying NASA JSC of all conjunctions with objects that come within a 5km x 25km x 5km ellipsoid of the Space Shuttle
 - USSTRATCOM trying to obtain extra tracking on the these close conjunctors
 - NASA JSC performing an avoidance maneuver when the flight rule criteria were met
- Debris avoidance maneuvers were typically less than 2 ft/sec, and if there was sufficient lead time, were scheduled to avoid perturbing scheduled mission objectives



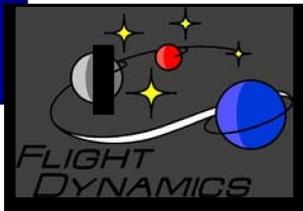
Space Station Collision Avoidance and Warning

- As NASA began planning for the Space Station Freedom Program, strategies for protecting the Space Station began to be examined
- This led to a three prong approach to addressing and mitigating the hazard:
 - For objects of 1cm or smaller, the Space Station was built to shield against penetration by these objects which could cause damage to the critical systems and habitable volumes of the vehicle
 - Objects between 1cm and 10cm that are too big to shield against and too small to be tracked
 - For these objects the Space Station Program pursued a passive orbital debris warning system to be installed on the Space Station
 - Envisioned to use a combination of scanning in the thermal infrared and visible spectra to detect incoming debris objects
 - Overall goal of the system was to provide the crew approximately 100 seconds of warning time before impact. However, this system was never developed nor implemented
 - For the trackable objects greater than 10cm in size, the proposal was to avoid these objects by performing a debris avoidance maneuver



Probability Method

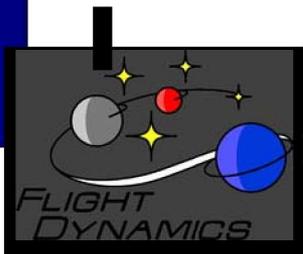
- In the early 90's, as the International Space Station (ISS) Program was nearing its first element launch, NASA JSC realized an approach more sophisticated than the box method would be required to protect the Space Station. This was driven by several factors:
 - Length of the Space Station mission meant that the exposure time would be several orders of magnitude greater than the Space Shuttle
 - Space Station is much larger than the Space Shuttle and much less maneuverable requiring greater lead times to effectively maneuver away from the debris object
 - Operational complexity of Space Station was also a factor with high maneuver rates causing unacceptable impacts to ISS Extra Vehicular Activities (EVA) and microgravity operations
 - Projected growth of the debris population
 - Operating altitude of Space Station meant it would see more debris flux than a typical Space Shuttle mission



Probability Method

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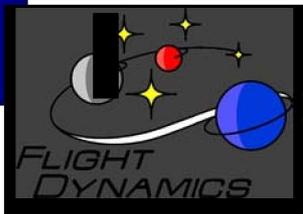
- These factors led to exploring options for using the debris and ISS uncertainty information to calculate the specific risk, or P_c , for each event at the Time of Closest Approach (TCA)
- Termed the “probability method”, this process, and the associated software, was developed by NASA JSC in conjunction with USSTRATCOM
 - Data for calculating P_c consists of both a state vector and state error covariance matrix for both the debris object and the Space Station (or Space Shuttle)
 - USSTRATCOM provides the data for the Space Station and debris objects, while NASA JSC provides the information for the Space Shuttle
 - USSTRATCOM also maintains the debris catalog and performs a screening process that recognizes close approaches between debris objects and our manned vehicles
 - When a close approach is recognized, USSTRATCOM delivers the state vector and covariance information to the NASA JSC flight controllers



Probability Method

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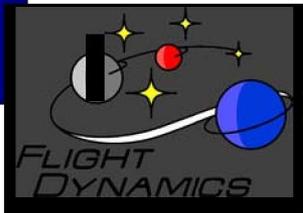
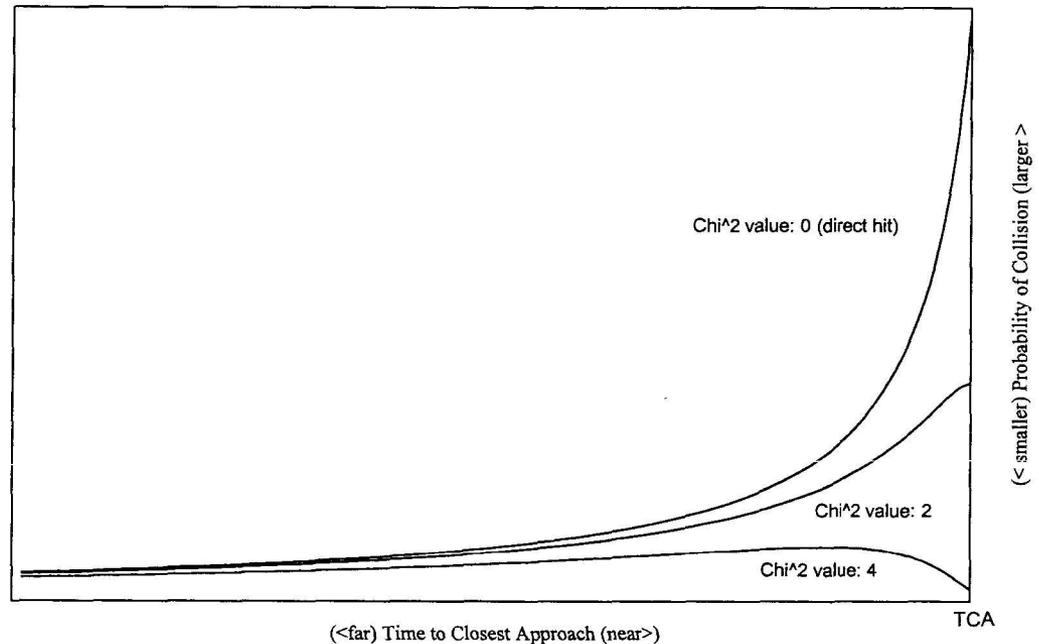
- The MCC flight controllers use a set of certified software tools to calculate and evaluate the P_c
 - The data is transformed into a single relative state and relative state error covariance matrix
 - This information is then used to calculate a two dimensional probability density function in the collision plane reference frame
 - The last component of the calculation is the projection of the manned vehicle area onto the collision plane
 - In practice a slightly conservative circular area is used for ease of calculation and to account for the size of the debris object
 - With this information a P_c can now be calculated



Probability Method

(concluded)

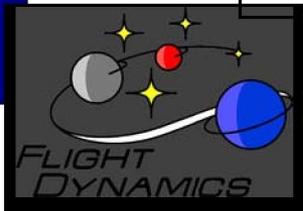
- It is important to realize that the Pc calculation is a point estimate of the risk based on the state and covariance information that were utilized
- This leads to an expected time-dependent behavior of Pc as we get closer to TCA due to:
 - better state information through increased tracking
 - reduced propagation time between the Pc calculation and TCA.



Space Station/Space Shuttle Probability Method Implementation

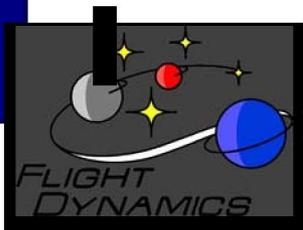
- With the adoption of the probability method, new risk thresholds had to be agreed to by the Space Station and Space Shuttle Programs
- Predicted maneuver rate and risk reduction that a number of different thresholds would provide for ISS are shown here:

Predicted Annual Debris Avoidance Maneuvers	Annual Collision Risk from Tracked Objects	Pc Maneuver Threshold	Risk Reduction from Zero Maneuver Case
0	~0.00065	N/A	N/A
~0.2	~0.00014	10^{-3}	~78%
~0.4	~0.00010	3×10^{-4}	~82%
~1.2	~0.00008	10^{-4}	~86%
~2.1	~0.00007	3×10^{-5}	~88%
~6	~0.00006	6×10^{-6}	~89%



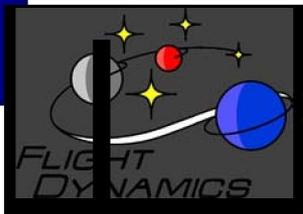
Space Station/Space Shuttle Probability Method Implementation (concluded)

- From this information a two-tiered debris avoidance criterion was developed
 - If the Pc violates the red threshold then a maneuver will be performed
 - If the Pc violates the yellow threshold then a maneuver will be performed if it doesn't compromise mission objectives
- The initial recommendations to the ISS Program for the red and yellow thresholds were 3×10^{-4} and 6×10^{-6} respectively
 - The final thresholds were set at 10^{-4} for red and 10^{-5} for yellow
 - Subsequently, the Space Shuttle Program adopted the same thresholds



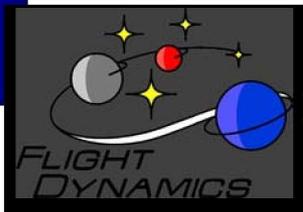
Probability Method Improvements

- After the initial implementation of the probability method, USSTRATCOM came to NASA looking for co-sponsorship of a project to improve its ability to derive navigation states and accurately propagate them
- This project was called the High Accuracy Satellite Drag Model (HASDM) with a stated goal of improving USSTRATCOM's ability to meet high accuracy space surveillance requirements for satellite trajectory prediction
- The HASDM approach processes drag information from the trajectories of 75 to 80 inactive payloads and debris (calibration satellites) to solve for a dynamically changing global correction to the thermospheric and exospheric neutral density
- Demonstration tests in 2001 & 2002 yielded excellent results and led to the operational implementation of HASDM
- Subsequent to HASDM, NASA helped sponsor two additional improvement projects: Sapphire Dragon and Fiery Dragon
 - These projects improved the navigation and propagation process by further refining drag curves, density modeling, and frontal areas variations
 - Although the results from these projects have not been fully implemented into operations, the additional improvements beyond HASDM resulted in the Jacchia-Bowman 2006/2008 (JB2006/2008) neutral atmosphere models



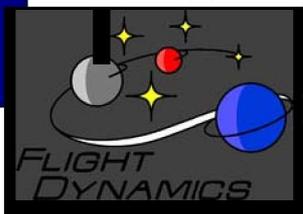
Recent Space Station/Space Shuttle Experience

- The selection of 10^{-4} and 10^{-5} for the red and yellow thresholds respectively yielded an expectation that our ISS maneuver rates would be around one maneuver per year
- In reality, our flight experience over the past 10 years shows a significantly lower rate than one maneuver per year
 - From 1998 to 2007 the ISS performed only 4 debris avoidance maneuvers
 - During that same period, we experienced an average of 3 conjunctions per month on ISS and an average of 2 conjunctions per mission on the Space Shuttle
 - In this context a conjunction is defined as an object predicted to be within the screening volume, currently a 4km x 50km x 50km box
- The environment changed significantly in 2008 primarily due to the breakup of COSMOS 2421
 - In 2008 and 2009 we experienced an average of 10 conjunctions per month on ISS and an average of 7 conjunctions per mission on the Space Shuttle
 - We executed the first ISS debris avoidance maneuver since 2003 in October 2008 and performed another mated Space Shuttle/ISS debris avoidance maneuver in March 2009



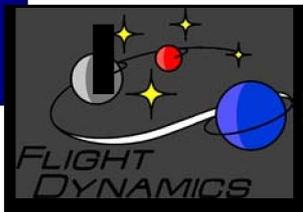
GSFC's Robotic Spacecraft Probability Method Implementation

- In 2004, in response to the growing debris risk, NASA GSFC implemented a process for providing routine collision avoidance operations to protect the Earth Science Constellations
 - The missions are managed independently by several different NASA centers as well as International Partners, but the mission operators work together to ensure the health and safety of the constellations
 - NASA JSC provided assistance in establishing the robotic process, which needed to be somewhat different from the manned process due to the different orbit regimes and different operations processes
- In August 2007, because of the increasing threat posed by orbital debris, NASA established a policy that requires routine collision avoidance operations for robotic assets that have maneuvering capability
- In April 2009, the policy was expanded to require routine conjunction analysis for non-maneuverable and non-operational NASA assets in addition to the maneuverable assets
 - Therefore the NASA Robotic Conjunction Assessment process has expanded and is currently being used to support 79 spacecraft in a variety of orbit regimes



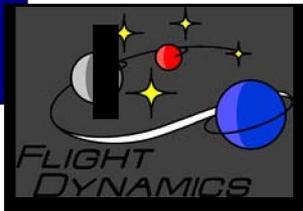
Future Considerations

- As we head into the future, the process of successfully avoiding orbital debris will undoubtedly continue to evolve
- If the number of trackable debris objects continues to grow NASA may reach a point where we will be forced to re-address some of the basic risk trades that have guided us to this point
- For example, if the trackable debris population were to grow by an order of magnitude, that would create a situation our current processes and staffing aren't designed to handle
- Potential changes include:
 - More automation and remote operations for handling the volume of conjunctions
 - Increased emphasis on improving the tracking accuracy of the debris objects through future improvements to the navigation filtering/propagation techniques as a follow-on to HASDM



Conclusion

- NASA has successfully used debris avoidance maneuvers to protect our spacecraft for more than 20 years
- This process which started out using parametric data and maneuver boxes has seen considerable evolution and now allows us to continue nominal operations for all but the most threatening objects
- This has greatly reduced the interruptions to the critical mission objectives being pursued by NASA's Space Station, Space Shuttle, and robotic satellites



Questions?

